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A Visual Evaluation Near the Threshold of Acuity of Five Color Liquid-Crystal Flat-Panel Displays

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Five color liquid crystal displays (LCDs) were perceptually evaluated near the threshold of visual acuity in a letter identification task. Stimuli consisted of all 26 capital letters of the Roman alphabet in either a 5X5 or 7X7 matrix. The subject's task was to identify the correct letter by entering the letter on a computer keyboard. The experimental design required all five subjects to be well-practiced touch typists. The LCDs were matched for luminance and contrast of test targets and target image size. For each size of letter matrix, evaluations occurred over three distances: near, medium, and far. The far condition corresponded to about a Snellen 20/17 line. Visual performance was acceptable, and, even at the far condition, only a 14 percent error rate occurred. The displays with the smallest fill factor scored highest overall. In addition, two of the displays had diffusion screens placed over the display by the manufacturer. The blur caused by the diffusion screen did not hurt performance and, indeed, may have helped it under the conditions of the test. Noise arising from light passage in off pixels appeared to hurt visual acuity, even though display contrast was controlled.

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Introduction

Flat panel display technology provides an alternative electro-optical display solution in applications that generally have relied upon cathode ray tube (CRT) technology. The introduction of flat panel displays into U.S. Army military aircraft is in progress. Flat panel displays offer several advantages over the older CRT technology. Flat panels are lighter in weight, lower in cost, lower in power consumption, and smaller in size.

In this study, the United States Army Aeromedical Research Laboratory (USAARL) evaluated five color liquid-crystal displays (LCDs) on the basis of their pixel structure. Four of the displays were active matrix while the other one was passive matrix. The evaluation consisted of equating the five displays for background and target luminance and viewing distance, so as to assess visual acuity as a function of pixel and target geometry. A physical evaluation of each display was completed in which pixel geometries, display resolution, luminance response, luminance uniformity, contrast, and viewing angle were examined. Some of these data are presented elsewhere (Harding,et al., 1997).

Methods

Displays. Five color LCDs were used in this study. Table 1 provides a listing of these displays along with some of their characteristics. In the body of the paper we will identify the particular panel by its ID.

Table 1.
Listing of the five active matrix displays and their particulars.

ID	Model #	Manufacturer	Matrix Type	Format (pixels)	Active Area (mm)
CP-1	PV440	PixelVision	Active	640 X 480	210.82 X 157.48
CP-2	LQ9D161	Sharp	Active	640 X 480	170.9 X 129.6
CP-3	LQ10DH15	Sharp	Active	640 X 480	211.2 X 158.4
CP-4	LM64C35P	Sharp	Passive	640 X 480	214.2 X 158.4
CP-5	LM64C21P	Sharp	Active	640 X 480	173.0 X 132.4

Psychophysical stimuli. We developed two sets of visual stimuli. Each set consisted of one each of the 26 capitalized letters of the Roman alphabet. The two sets differed by their pixel matrices, one was a 5X5 and the other was a 7X7 matrix. The geometry of each letter is shown in Figure 1. In the 5X5 set, each letter was five pixels wide and five pixels high, and likewise in

the 7X7 set, each letter was seven pixels wide and seven pixels high. In the 5X5 set, some letters differed by only one pixel (e.g., the letters 'C' and 'O'). The minimum difference increased to two pixels in the 7X7 set as with the letters 'D' and 'O'.

Stimulus duration ended when a keyboard response was made. Faster keyboard responses resulted in shorter durations of letters. For each letter, about 5 seconds were allowed for a response. If a response was not made, the letter was turned off and the screen was blanked for a timeout period which lasted about 2 seconds. A tone signaled the end of the timeout and a new letter was then presented.

Subjects. Five observers (two males and three females) with normal vision were used in this study. The ages of the subjects ranged from 25 to 31 years. To assure that each observer was well practiced with the task and was familiar with the letter geometries, each observer, prior to the experiment, was given a copy of the experimental software so that they could run simulations of the experiment on their own personal computers. Each observer was allowed to participate when they achieved a perfect score on three consecutive trials at a normal computer monitor viewing distance.

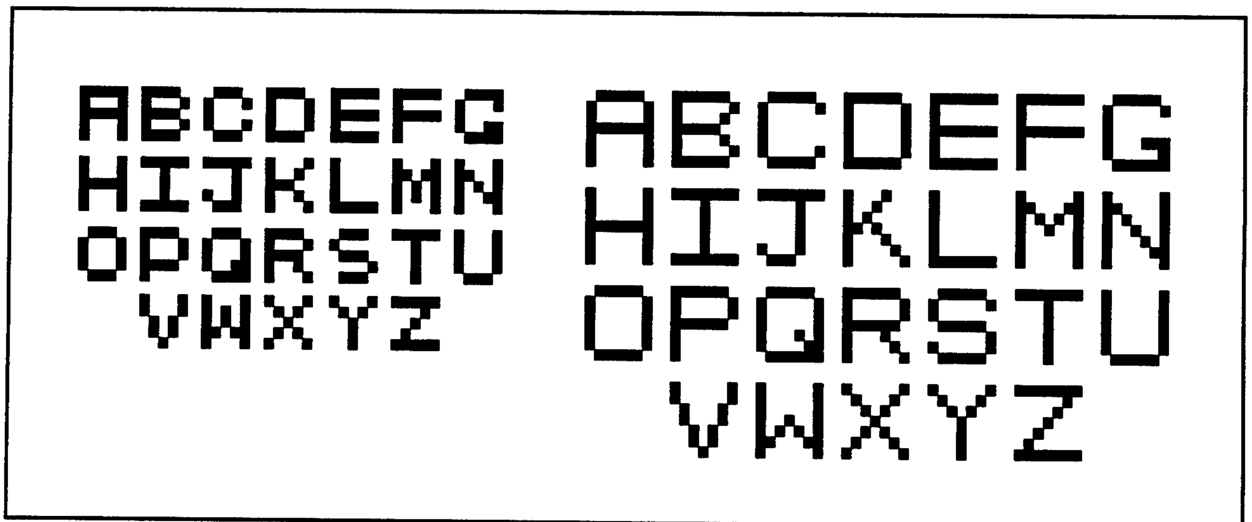

Figure 1. Alphabetical letters created for the psychophysical experiment. Alphabet on left is composed of 5X5 pixels and alphabet on right is composed of 7X7 pixels.

In order to obtain a comfortable typing position, the subjects' chair and keyboard position were adjusted to mimic their typical typing posture. While in the typing position, a chin rest was positioned under their chin to maintain head position. The chin rest was attached to an optical bench upon which the displays were mounted. The height of each display was adjusted to coincide eye level with the center of the display.

Pixel pitch and viewing distance. Three viewing distances were used in this study (near, medium, and far). In order to equate displays for target size, we measured each display's pixel

pitch and calculated the required distances for the three viewing distances. Table 2 shows the viewing distances and pixel pitch for each of the displays. The distances for the 5X5 and 7X7 letters were chosen so that the letters subtended the same visual angle. For example, letters in the 5X5 near and 7X7 near subtended the same visual angle. (*Please note that the flat panel used in CP-1 is the same flat panel used in CP-3, except for the presence of the diffusing screen. The differences in pixel pitch can be attributed to measurement error and to blurring caused by CP-1's diffusing screen [see below].*)

Table 2.
Viewing distances for the five flat panel displays (given in centimeters).

		5X5 Letter Matrix			7X7 Letter Matrix		
ID	Pixel Pitch	Near	Medium	Far	Near	Medium	Far
CP-1	0.3291 mm	90.0	112.5	135.0	126.0	157.5	189.0
CP-2	0.2681 mm	73.3	91.6	110.0	102.6	128.3	154.0
CP-3	0.3296 mm	90.1	112.7	135.2	126.2	157.7	189.3
CP-4	0.3250 mm	88.9	111.1	133.3	124.4	155.5	186.7
CP-5	0.2550 mm	69.7	87.2	104.6	97.6	122.0	146.4

Test design. To counter learning and like variables which could affect our results, a counter balanced design was developed. The design (Table 3) called for each subject to start their testing with a different display. Also, on all subsequent days of testing, no two subjects tested on the same display.

Table 3.
Counterbalanced design for subject-display-day interaction.

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9
Subject 1	CP-1	CP-2	CP-3	CP-4	CP-5				
Subject 2		CP-2	CP-3	CP-4	CP-5	CP-1			
Subject 3			CP-3	CP-4	CP-5	CP-1	CP-2		
Subject 4				CP-4	CP-5	CP-1	CP-2	CP-3	
Subject 5					CP-5	CP-1	CP-2	CP-3	CP-4

A subject viewed only one display during each day's session. At each of the 5X5 and 7X7 distances, three trial sessions were conducted. Each trial consisted of a pseudo-random presentation of each of the 26 letters of the alphabet and then a second presentation of each of the 26 letters of the alphabet. Thus, 52 observations per trial and 3 trials per distance, for a total of 18 trials per subject-day were completed. Since subjects continued at their own pace, with the exception of required rest periods between conditions, most sessions lasted approximately 1 hour or less. In all, 23,400 observations were recorded (52 observations per trial x 3 trials per conditions x 3 distances x 2 letter sizes x 5 displays x 5 subjects).

Equating contrast and luminance of display targets. To control for luminance and contrast of target letters across displays, we measured the luminance response functions for a target letter as a function of gray level. Our gray level range was from 0 to 255 in 16 incremental steps. Figure 2 shows a plot of luminance response functions for each of the five displays. Please note that the luminance response function for CP-3 was multi-valued and, as CP-1 and CP-3 used identical displays (with the exception of the passive diffusion screen), there is no plausible explanation for the discrepancy. Since the luminances at only two points were used in these experiments (i.e., target and background luminances), the response behavior of CP-3 did not affect the outcome of these experiments.

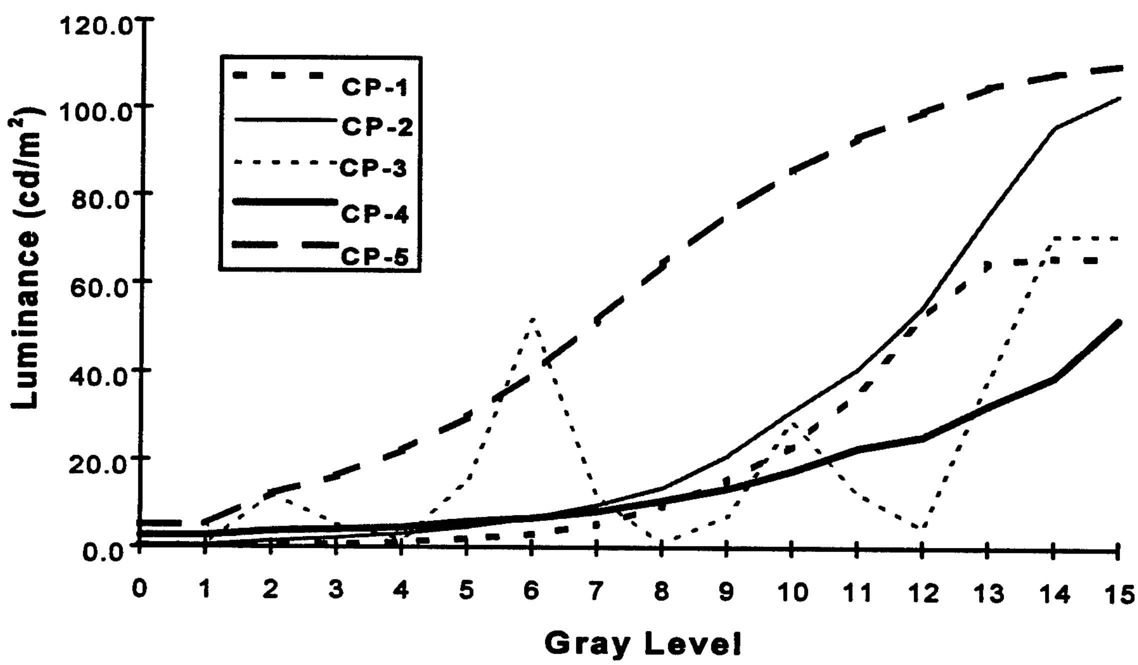

Figure 2. Luminance response functions as a function of computer gray level for the five flat panel displays.

Table 4 provides a summary of the luminance values and contrast ratios achieved with the five displays. Although equality was not achieved, a fairly reasonable luminance and contrast match was achieved in order to compare display pixel features. Figure 3 provides a graphical representation of each display's target and background luminances.

Table 4.
Summary of target and background luminances used in the acuity study.
Target and background luminances are given in cd/m^2.

Displays ID	Target Gray Level	Background Gray Level	Target Luminance	Background Luminance	Contrast Ratio
CP-1	12	7	52.6	5.2	10.1
CP-2	12	5	55.0	4.6	12.0
CP-3	6	3	51.8	5.2	10.0
CP-4	15	5	52.2	5.8	9.0
CP-5	7	1	51.8	5.1	10.2

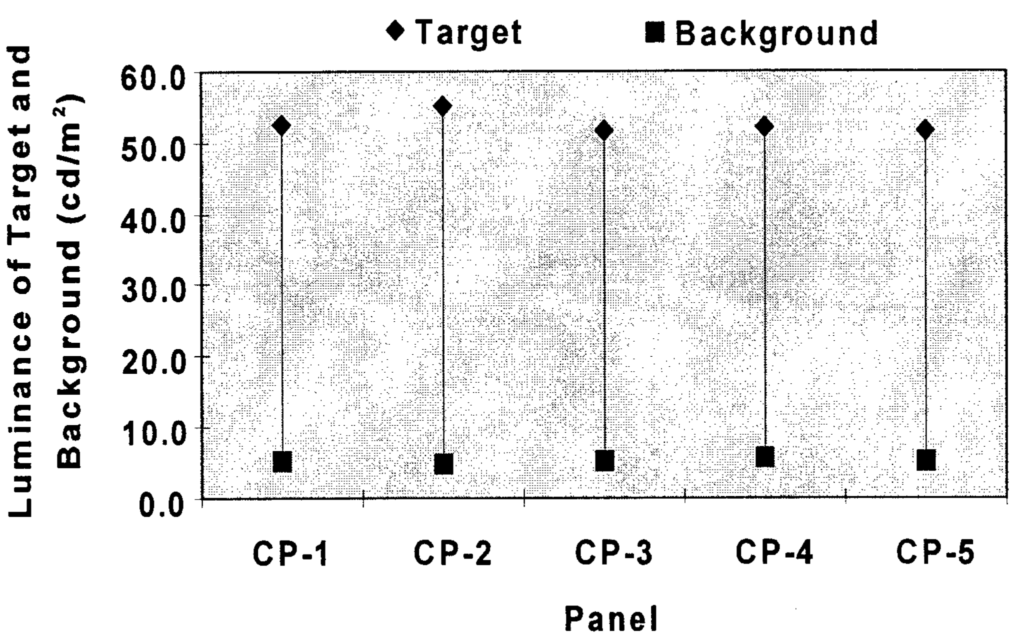

Figure 3. Target and background luminance for five flat panel displays.

Image size, pixel geometry, diffusion and fill factor. The viewing distances described in Table 2 for each of the displays provide for a constant image size across all of the displays. In the psychophysical experiments, an effort was made to maintain equal viewing conditions among the displays, with the only differences relating to display pixel geometry and the clarity of pixels. Figure 4 shows a rendition of the 5X5 letter 'E' with nominal color pixel geometry. Distance G is equal to pixel pitch and distance S equals five times the pixel pitch. Table 5 provides the accompanying measurement data for Figure 4.

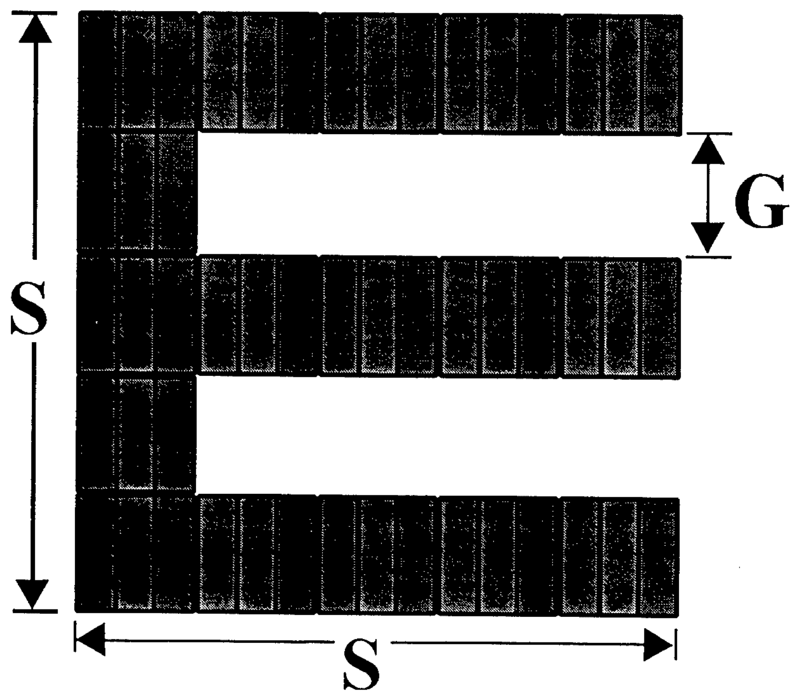

Figure 4. Nominal geometry of the 5X5 letter E. The distance G equals the pixel pitch and the distance S equals five times the pixel pitch. For the purpose of the of this illustration, the fill factor is 1; that is, the subpixels occupy all of the alloted pixel space.

Table 5.
Visual angle of distances S and G in Figure 4 measured in degrees.

Distance	Near 5X5	Mid 5X5	Far 5X5	Near 7X7	Mid 7X7	Far 7X7
S	0.1048	0.0838	0.0698	0.1048	0.0838	0.0698
G	0.0210	0.0168	0.0140	0.0299	0.0239	0.0200

With certain liberties, the letter stimuli can be related to Snellen letters using the measurement for the pixel pitch as the acuity gap. In this fashion, an approximate Snellen letter size can be established for the three distances and two letter sizes. Figure 5 shows the Snellen equivalent line for each of the stimulus conditions. Although the 5X5 and the 7X7 letters subtend the same visual angle, their gaps are significantly different and ease of viewing should be considerably less with the 7X7 letter sizes.

Color Plate 1 (Appendix A) shows photographs taken of the 5X5 and 7X7 letter 'E' for each of the displays. From the photographs, the differences in pixel geometry and clarity are readily apparent. In essence, there are two distinct pixel geometries: the pixel geometry observed in CP-1 and CP-3 (with identical flat panels), and the pixel geometry observed in CP-2, CP-4 and CP-5. The obvious difference between CP-1 and CP-3 is that the pixels in CP-1 are blurred intentionally by the manufacturer using a diffusing screen placed over the panel itself. Likewise, CP-2 is blurred using a diffusing screen.

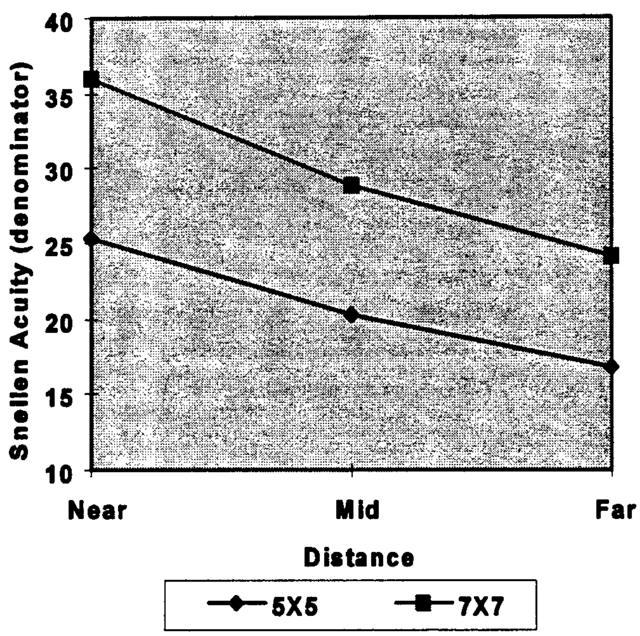

Figure 5. Equivalent Snellen acuity line for the stimulus conditions.

The fill factor for each of the flat panels was measured using photomicrographs like those shown in Color Plate 1 (Appendix A). Fill factor is a measure of the area of the active pixels or subpixels to the total area. It is a factor that affects the overall resolution of flat panel displays (Infante, 1993). Displays with smaller fill factors provide for a higher resolution as measured by the display modulation transfer function (MTF). Mathematically, the fill factor is the active pixel area divided by the total area. Table 6 shows the fill factors measured for each of the displays.

CP-2 was considerably difficult to measure due to its blur and, therefore, the accuracy of this measurement is highly suspect.

Table 6.
Measured fill factors for each of the flat panel displays.

Flat Panel	CP-1	CP-2	CP-3	CP-4	CP-5
Fill Factor	0.61	0.70	0.61	0.80	0.74

Visual acuity of test observers. To compare experimental results with known behavior, visual acuity was assessed at three viewing distances using the Graham-Field acuity chart. At each distance, the observer was asked to read the smallest letter sized paragraph that they could read. Through a series of approximations, we chose the paragraph (acuity level) where few mistakes were made in their reading, and the subject appeared to be able to read the paragraph with slight effort. In Figure 6, we plot the acuity values obtained for each subject.

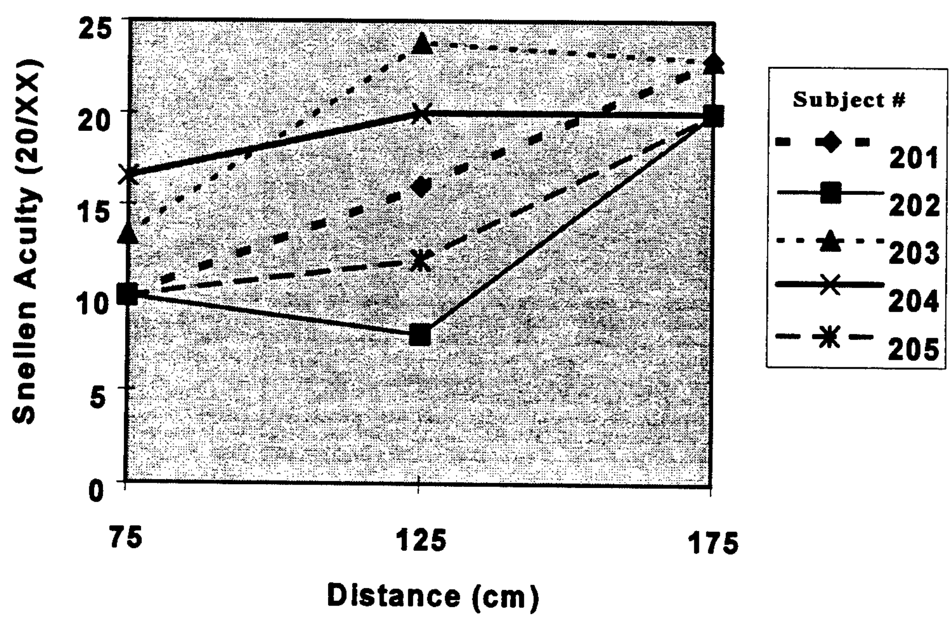

Figure 6. Acuity measured as a function of three viewing distances. Note that acuity is very good for all subjects at the nearest viewing distance and increases to a Snellen acuity of 20/20 or worse at the far viewing distance. In general there was an inverse relationship between acuity and distance. The middle distance acuities for subjects 202 and 203 were the exceptions to the rule. For these subjects, the middle distance acuities were puzzling. Subject 202 had better acuity at the 125 cm distance than at the near 75 cm distance. On the other hand, subject 203 had better acuity at 175 cm than at the 125 cm distance. Acuities were measured with the Graham-Field acuity chart.

Results

Summary data collected from all five subjects are presented as tables in Appendix B. From a cursory viewing of the data, it may be said that the majority of errors made in letter recognition were made due to a failure to clearly recognize the letter, as opposed to errors made in typing. We believe this since, for the easiest condition, subjects made very few mistakes. For example, the average recognition performance for the 7X7 letters at the nearest viewing distance was 98.31 percent. This error rate equates to less than one error for every trial (i.e., for every 52 observations). In addition, for entry into this study, each subject had to complete three trials, at a comfortable viewing distance, without a single mistake. Thus, we can be confident that typing errors were minimal and accounted for less than 2 percent of the total error rate.

Each condition can be ranked by perceptual difficulty by averaging recognition performance across subjects and across displays. Figure 7 shows average scores collected for each of the conditions.

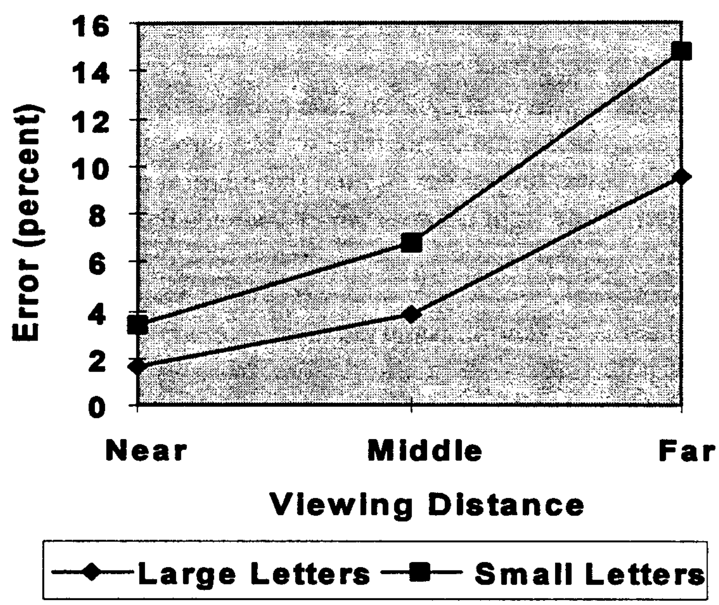

Figure 7. Average error rate for each of the stimulus conditions.
Data are averaged across displays and across subjects.

We immediately see that the error rate, as expected, increases with increases in distance. Also, it was observed that the small letters with the minimum of one pixel gap were harder to identify correctly than the large letters with the minimum of two pixel gap, even though at each distance, the large and small letters subtended the same visual angle. The reason for the difference lies in the ratio of the letters' gap width to its stroke width. Stroke width in this case is the diameter of the liquid crystal (i.e., subpixel arrangement). This particular issue will be discussed further below.

Acuity considerations. In Figure 5, the predicted equivalent Snellen acuity line is shown for each stimulus condition. These curves are based on the nominal measurements shown in Table 5. These figures assume that the fill factor of each display is 1.0. From our measurements of fill factor, we know that each of the five displays had a fill factor considerably less than 1.0 (Table 6). However, from Figure 5 an ordered arrangement is seen with the 7X7 near condition being the simplest task and the 5X5 far condition being the hardest task. As observed in Figure 7, these two expectations were met. However, expectations for the other data points did not fare as well. The reason for this failure lies with two main factors. First, a Snellen eye chart does not present all letters of the alphabet, but rather presents those letters that have more or less equal legibility. That is to say, each letter has a gap which is critical for recognition, and these gaps are the same size. To better test natural viewing conditions and to use the data for predictive models, we used all 26 capital letters and obviously letters with different legibilities. The question of letter legibility is addressed in a companion paper (Harding et al., 1997). As an example, we can clearly see that the letter 'L,' which doesn't contain a small gap as does the letter 'C,' must be easier to recognize. Second, each letter in a Snellen line has equal stroke width. In our study we have grouped data from five displays which have a range of fill factors which can be likened to stroke width and gap width. Since the data plotted in Figure 5 are based upon nominal data instead of measured data, the predictions may be in error (see MTF factor effects below). Another consideration is the contrast provided by a Snellen eye chart which consists of crisp black letters on a solid white chart. LCDs modulate light by changing the conformity of their crystals. The conformation has a polarizing effect and the modulation can be likened to crossed polarizers. In the closed position, some light escapes which reduces the overall contrast of the image.

Display performance. In general, psychophysical performance across the five displays was quite good. However, it might be beneficial to rank order each display to see if there are certain physical characteristics that could account for subtle perceptual differences. Figure 8 shows overall psychophysical performance with each of the displays. The data represent averages obtained across all three viewing distances and all five subjects for each of the two letter sizes. It is interesting to note that two of the three best displays are displays CP-1 and CP-2. As shown in the color plate in Appendix A, the photomicrographs for these two displays are blurred. The reason for this is that the manufacturer placed a diffusion screen directly over the display. This diffusion causes a general blurring of the image which may cause similar perceptual benefits as those seen with the Guassian phosphor blur observed in CRT displays. This technique limits perceptual aliasing from unwanted higher spatial harmonics. It is also interesting to note that the two worst displays, CP-4 and CP-5, had similar pixel geometry, and these displays also had significant noise levels not apparent in the other displays. In addition, the pixel geometry of these two displays had the highest fill factor (see Table 6) of any of the other displays. As we know from the work of Infante (1993), a high fill factor causes a more rapid fall-off of the display's MTF. Noise is apparent in the photomicrographs of CP-4 and CP-5 and is in the form of light bleed-through from adjacent off pixels. After a careful examination, it was observed that the noise level in CP-5 was obviously greater than that in CP-4 and may have contributed to that display's poorer performance.

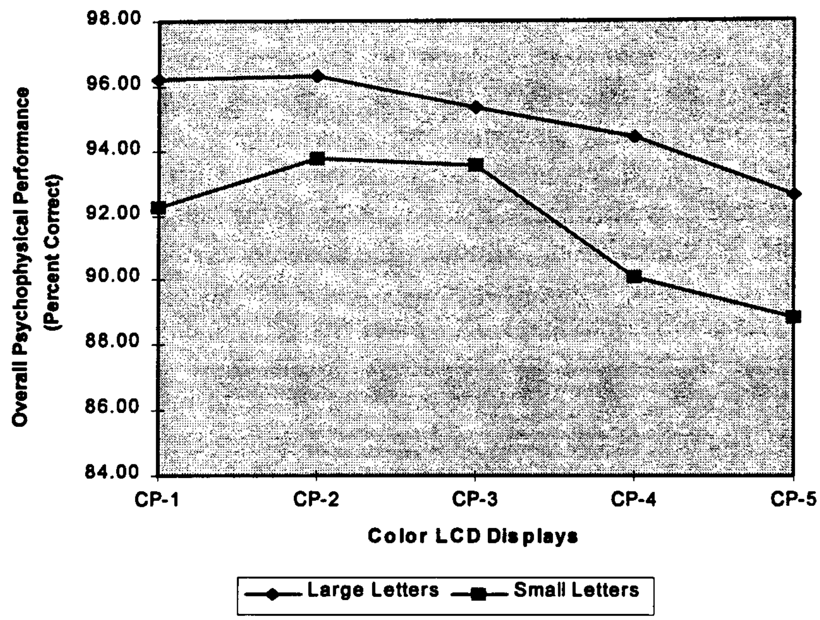

Figure 8. Overall psychophysical performance on each of the color displays. Each data point represents the average performance scored across all three viewing distances and all five subjects.

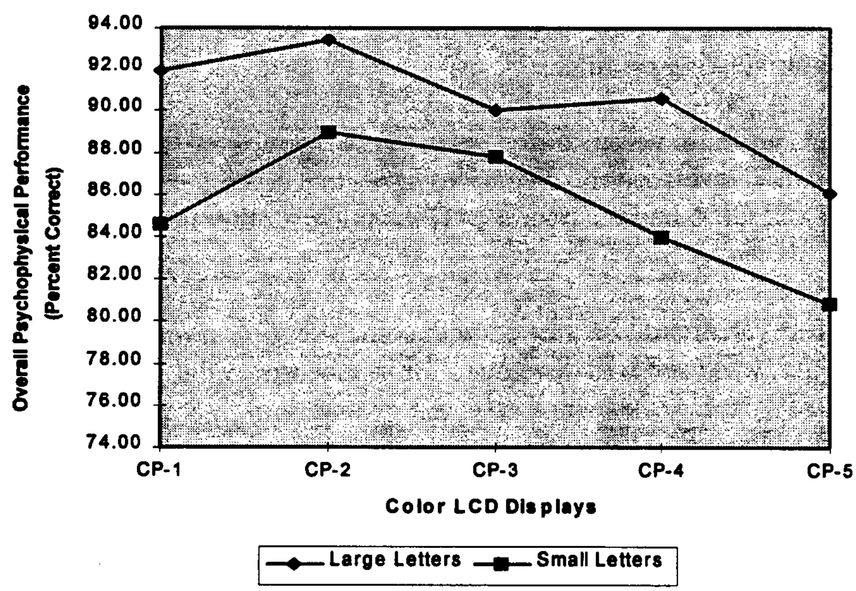

Figure 9. Overall psychophysical performance at the furthest viewing distance for each of the displays. The data were averaged across all five subjects.

It would be beneficial to examine overall display performance at the furthest viewing distances to investigate display quality under demanding visual requirements. Figure 9 shows data obtained for only the furthest viewing distance. The same general trend remains as observed in Figure 8, although two observations are clear. First, CP-2 was clearly the best display in the test, and secondly, CP-5 was clearly the worst display in the test. It is also interesting to compare CP-1 and CP-3, since the only difference between the two is the diffusion screen placed over CP-1. From figures 8 and 9, we see that CP-1 was better in the large letter condition and CP-3 was better in the small letter condition. Although the differences could be due to the randomness of the data, it is interesting to speculate that the blur of CP-1 may improve large object resolution (if one could argue that a 7X7 pixel character is large) and degrade finer object resolution. This point must, however, await further analysis.

Fill factor effects. The role of fill factor in display resolution can best be expressed by the MTF. The MTF of flat panel displays can be predicted based upon pixel density, spacing, and geometry (Barten, 1991, 1993; Infante, 1993). The MTF takes the form of a sinc function [sin(x) / x] and is expressed as:

$$MTF(\mu) = | \sin(\pi\sqrt{F_f}x_p\mu) / (\pi\sqrt{F_f}x_p\mu) | = | \sin(\pi x_a\mu) / (\pi x_a\mu) |$$

Where $x_a = \sqrt{F_f}x_p$

and μ is spatial frequency, F_f is fill factor, and x_p is the pixel pitch. Based upon our measurements of pixel pitch, Figure 10 shows the normalized MTFs for each of the color LCDs for the far small-letter viewing distance.

The MTFs show very little variation and, even at the Nyquist frequency, the modulation range is less than 10 percent. Nevertheless, the curves agree to a certain extent with the results of this paper, in that CP-4 and CP-5 had the poorer MTFs while the other three displays faired slightly better.

These MTFs, however, should be viewed with some skepticism for a variety of reasons. First, the MTF equation that was used was developed for monochrome flat panel displays and not color displays with their subpixel elements and different geometries. Second, two of the displays, CP-1 and CP-2, were intentionally blurred by the manufacturers by placing a diffusion screen over the pixel array. This diffusion causes a slight blurring of the image (see color plate in Appendix 1) and this blurring may cause similar perceptual benefits to the Guassian blur caused by CRT phosphor burn. In any case, the blur will surely influence the MTFs for these two panels, and therefore, the MTFs would show a faster fall-off in the high frequency range.

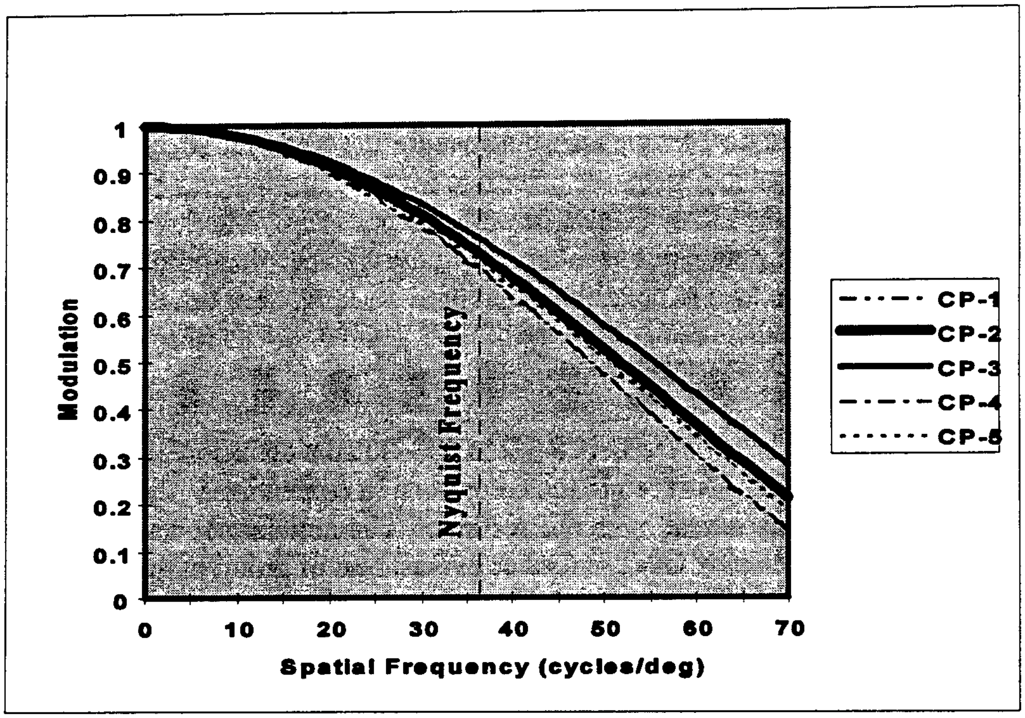

Figure 10. Predicted MTFs for each of the five color LCDs for the far 5X5 condition. The curves have been normalized to 1 at the 0 cycle/deg spatial frequency. The Nyquist frequency is plotted as a vertical line at approximately 36 cycles/deg. At the Nyquist frequency, the MTFs varied by less than 10 percent. The curves for CP-1 and CP-3 overlap.

Discussion

In this paper, we evaluated five LCDs in a letter recognition task. The five displays were balanced for luminance, contrast and target size. Five touch typists with excellent vision took part in this study. Their response data is the subject of two papers, with this paper being the first of the sequence. The second paper (Harding et al., 1997) will focus on legibility and letter recognition issues relating to the geometry of letters. This paper rated the five displays near the threshold of recognition and found several display factors that may influence recognition.

Certain facts begin to fall-out from only a tertiary examination of the data. The five subjects were visually challenged by the furthest viewing distances and misidentified the 5X5 letters more often than the 7X7 letters even though the letters subtended the same visual angle. There are several reasons for this. Acuity has a relatively steep fall-off near the threshold. We attempted to challenge the subjects while still maintaining a high performance level, and the data confirm this approach. For letters well above threshold, they can be clearly seen regardless of their size. Near the resolution threshold, visual performance begins to fall-off rather rapidly. Only a small

decrease in letter size can produce large changes in performance. Using the letter stimuli at a viewing distance equivalent to about a Snellen 20/17 line, an approximate 14 percent error rate was found. If the study had extended to a distance equivalent to the 20/10 mark, for example, it would be expected that most observers would approach chance performance. As can be seen in tables B-1 through B-5, at the furthest viewing distance for the 5X5 matrix (equivalent to the 20/17 line based upon nominal gap size), the error rate for each display was between 10 to 20 percent. Given 26 letters in the alphabet, chance performance is only about 4 percent, or a 96 percent error rate. However, we are not as interested in the distance that produces mere chance behavior but are instead interested in conditions that produce unreliable behavior. The smaller letters were harder to distinguish mainly because of their smaller gap widths since the matrices had the same stroke width (width of one pixel).

Two of the displays tested in this study (CP-1 and CP-2) had a diffusion screen placed over the display by the manufacturer. As seen in the color plate in Appendix A, the pixels appeared blurred and the subpixel borders were harder to accurately characterize. It was therefore somewhat of a surprise that display CP-2 ranked as overall best of group in this study. Further, CP-1 and CP-3 tied for second. The two displays were identical with the exception of the diffusion filter placed over CP-1. Display CP-1 had higher scores with the 7X7 letter matrix and CP-3 had higher scores with the 5X5 matrix. We are not certain whether anything should be made of these results. We can say that the diffusion screens did not hinder recognition and even may have helped by filtering out unwanted higher frequency noise.

Displays CP-5 and CP-4 ranked poorer than the other three displays. Both displays had similar pixel geometry and had the highest fill factor. In addition, both displays suffered from noise arising from light leakage from off pixels (see the photomicrographs in Appendix A).

In conclusion, we tested displays at their resolution limit (small characters) under conditions that would generally not arise during the course of routine observation. Given the normal scatter inherent in psychophysical data of this kind, the data variability reported here relate almost entirely to display parameters such as pixel geometry, pixel noise (mainly CP-5 and CP-4) and screen filter characteristics (display CP-1 and CP-2 only), since we controlled for image size, contrast and luminance of targets.

References

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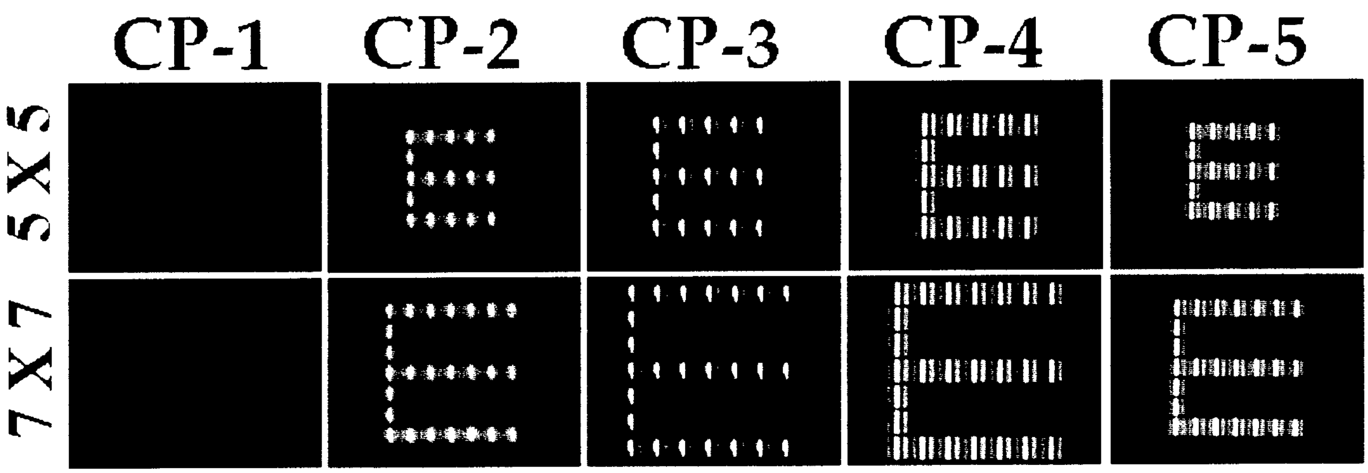
Appendix A.

Color plate of the letter E

Each image is a photomicrograph of the 5X5 and 7X7 letter 'E' as displayed on each of the color displays.



Appendix B.

Data tables for each subject and for each panel

The data are represented as a percent correct response for each condition. As discussed in the methods section, three separate trials were completed for each condition where each trial consisted of 52 observations (each letter presented twice in random order). Thus, the percent correct data presented in the tables are for a total of 156 independent observations. For example in table B-1, subject 201 had a percent correct of 99.36 for the near 7X7 condition. This represents only 1 misidentification in 156 observations.

Table B-1.
Percent correct responses for display CP-1.

Letter Size	Viewing Distance	Subject 201	202	203	204	205	Average
Large	Near	99.36	99.36	98.72	98.08	99.36	98.98
	Middle	95.51	97.44	96.80	99.36	99.36	97.69
	Far	95.51	87.82	89.10	92.95	94.23	91.92
Small	Near	96.79	97.76	98.72	96.15	100.00	97.88
	Middle	98.08	92.31	89.74	97.44	93.59	94.23
	Far	84.61	79.49	78.85	92.95	87.18	84.62

Table B-2.
Percent correct responses for display CP-2.

Letter Size	Viewing Distance	Subject 201	202	203	204	205	Average
Large	Near	99.36	97.44	96.79	100.00	98.72	98.46
	Middle	98.08	96.15	92.95	98.72	99.36	97.05
	Far	96.15	92.31	88.46	92.95	97.44	93.46
Small	Near	100.00	98.08	92.95	99.36	99.35	97.95
	Middle	98.08	94.87	82.69	97.44	98.72	94.36
	Far	97.44	85.26	72.44	96.79	92.95	88.98

Table B-3.
Percent correct responses for display CP-3.

Letter Size	Viewing Distance	Subject 201	202	203	204	205	Average
Large	Near	100.00	98.08	97.43	99.36	100.00	98.97
	Middle	99.36	92.31	96.16	97.44	100.00	97.05
	Far	86.54	87.82	86.54	91.66	97.43	90.00
Small	Near	99.36	94.87	97.44	98.72	100.00	98.08
	Middle	99.36	88.46	89.74	96.15	100.00	94.74
	Far	92.95	82.69	82.05	91.67	89.74	87.82

Table B-4.
Percent correct responses for display CP-4.

Letter Size	Viewing Distance	Subject 201	202	203	204	205	Average
Large	Near	99.36	98.72	98.08	91.03	100.00	97.44
	Middle	96.79	94.23	99.36	85.90	99.36	95.13
	Far	94.87	91.02	91.67	76.28	99.36	90.64
Small	Near	98.08	91.67	98.08	83.97	99.36	94.23
	Middle	98.72	91.67	85.90	83.98	100.00	92.05
	Far	94.23	83.97	81.41	68.59	91.66	83.97

Table B-5.
Percent correct responses for display CP-5.

Letter Size	Viewing Distance	Subject 201	202	203	204	205	Average
Large	Near	98.08	96.80	98.08	95.51	100.00	97.69
	Middle	96.15	95.51	92.31	89.10	97.44	94.10
	Far	95.51	85.90	87.18	68.68	92.95	86.04
Small	Near	98.72	87.82	99.36	92.95	96.15	95.00
	Middle	99.36	83.33	89.89	84.61	95.51	90.54
	Far	91.67	75.00	77.56	73.72	86.54	80.90

Table B-6.
Percent correct responses across displays for subject #201.

Letter Size	Viewing Distance	Display CP-1	CP-2	CP-3	CP-4	CP-5	Average
Large	Near	99.36	99.36	100.00	99.36	98.08	99.23
	Middle	95.51	98.08	99.36	96.79	96.15	97.18
	Far	95.51	96.15	86.54	94.87	95.51	93.72
Small	Near	96.79	100.00	99.36	98.08	98.72	98.59
	Middle	98.08	98.08	99.36	98.72	99.36	98.72
	Far	84.61	97.44	92.95	94.23	91.67	92.18
	Average	94.98	98.19	96.26	97.01	96.58	96.60

Table B-7.
Percent correct responses across displays for subject #202.

Letter Size	Viewing Distance	Display CP-1	CP-2	CP-3	CP-4	CP-5	Average
Large	Near	99.36	97.44	98.08	98.72	96.80	98.08
	Middle	97.44	96.15	92.31	94.23	95.51	95.13
	Far	87.82	92.31	87.82	91.02	85.90	88.97
Small	Near	97.76	98.08	94.87	91.67	87.82	94.04
	Middle	92.31	94.87	88.46	91.67	83.33	90.13
	Far	79.49	85.26	82.69	83.97	75.00	81.28
	Average	92.36	94.02	90.71	91.88	87.39	91.27

Table B-8.
Percent correct responses across displays for subject #203.

Letter Size	Viewing Distance	Display CP-1	CP-2	CP-3	CP-4	CP-5	Average
Large	Near	98.72	96.79	97.43	98.08	98.08	97.82
	Middle	96.80	92.95	96.16	99.36	92.31	95.52
	Far	89.10	88.46	86.54	91.67	87.18	88.59
Small	Near	98.72	92.95	97.44	98.08	99.36	97.31
	Middle	89.74	82.69	89.74	85.90	89.89	87.59
	Far	78.85	72.44	82.05	81.41	77.56	78.46
	Average	91.99	87.71	91.56	92.42	90.73	90.88

Table B-9.
Percent correct responses across displays for subject #204.

Letter Size	Viewing Distance	Display CP-1	CP-2	CP-3	CP-4	CP-5	Average
Large	Near	98.08	100.00	99.36	91.03	95.51	96.80
	Middle	99.36	98.72	97.44	85.90	89.10	94.10
	Far	92.95	92.95	91.66	76.28	68.68	84.50
Small	Near	96.15	99.36	98.72	83.97	92.95	94.23
	Middle	97.44	97.44	96.15	83.98	84.61	91.92
	Far	92.95	96.79	91.67	68.59	73.72	84.74
	Average	96.16	97.54	95.83	81.63	84.10	91.05

Table B-10.
Percent correct responses across displays for subject #205.

Letter Size	Viewing Distance	Display CP-1	CP-2	CP-3	CP-4	CP-5	Average
Large	Near	99.36	98.72	100.00	100.00	100.00	99.62
	Middle	99.36	99.36	100.00	99.36	97.44	99.10
	Far	94.23	97.44	97.43	99.36	92.95	96.28
Small	Near	100.00	99.35	100.00	99.36	96.15	98.97
	Middle	93.59	98.72	100.00	100.00	95.51	97.56
	Far	87.18	92.95	89.74	91.66	86.54	89.61
	Average	95.62	97.76	97.86	98.29	94.77	96.86